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The Use of Superconductive Technology for Energy Storage and Power Transmission for Large Power Systems - Power Parks*

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I. INTRODUCTION

In many cases, the strategies for social and defense benefits as well as the electric power generation technologies proposed and discussed at this Forum lead inescapably to the concept of "power parks," where large amounts of power are produced in limited geographic zones remotely situat[illegible] from load centers. The question of what these power parks will look like - i.e., the pros and cons of the various generation technologies - has been a main concern for the Forum participants. The question, however, of what is done with the electric power once it is produced in huge amounts - primarily, how is it ultimately delivered to the user - is equally important but has not been so directly nor so thoroughly dealt with. We are concerned here with collective or individual power sources of 5,000 MW_e and above, and it is the purpose of this paper to suggest several ways in which a technology, not now in use in the electric power grid, may help in the efficient, reliable, and economic handling of those amounts of bulk power.

*Work performed under the auspices of the U.S. Department of Energy.

The technology we have in mind is superconductivity. Ever since its discovery in 1911, the phenomenon of superconductivity has given the promise of benefiting several critical areas of our society. But in every case so far, failure from one source or another has denied that promise. Hence superconductivity has remained a fascinating subject for the laboratory, for scientific investigation, and no doubt it will continue to be so for many years to come; but now it appears to us that the time is at hand to reap the technological rewards made possible by advances in the science of superconductivity.

It also appears to us that the electric power industry may be one of the first to employ superconductivity in several important applications. Activity toward this end is occurring in all the advanced nations of the world. For the generation of power through the developing technologies of MHD and magnetically confined fusion, superconducting magnets much larger and more complex than now available will be needed; and for large (> 1300 MVA) central power station generation, synchronous machines employing superconducting materials in the field windings of the rotors are considered highly attractive. For the transmission of bulk power both ac and dc superconducting cable systems are being developed worldwide in a number of laboratories. For the storage of energy to be used for peakshaving, load leveling, or system stabilization, superconducting magnets can be used advantageously. In addition, superconducting switches, transformers, and instrumentation devices are worthy of consideration.

In this paper, however, we will concentrate our attention upon direct current superconducting power transmission lines (dc SPTL) and superconductive magnetic energy storage (SMES) as appropriate systems for handling the large amounts of power likely to be generated at centralized sites remote from load centers. The Los Alamos Scientific Laboratory (LASL) is the only U.S. organization investigating and developing the dc SPTL (the Brookhaven National Laboratory is similarly undertaking the sole U.S. ac SPTL development). In the case of SMES, efforts at LASL are joined by complementary work at the University of Wisconsin. All of these efforts are being carried out under the auspices and funding support of the U.S. Department of Energy.

The necessity for introducing new technologies of power transmission and energy storage should be clear. Extension of present technologies can indeed help to alleviate some of the problems that are certain to be associated with the large electric power loads we are considering, but most of the methods now in use for transferring and managing power loads are being pushed to the limits of acceptability. Questions concerning the environmental and health aspects of extra high voltages, problems arising from land use restrictions for rights-of-way to accommodate large overhead transmission systems, need for conservation of fuel resources through increased network efficiency, demands for keeping capital costs within reason, and stringent requirements for electric power system reliability and safety - all these factors should provide sufficient incentive for seeking new, perhaps radically new, power technologies. Through applications of superconductivity, we can foresee excellent possibilities for successful solutions to many of those vexing problems and demands.

II. WHY SUPERCONDUCTIVE TRANSMISSION AND STORAGE?

Superconductors form a select class of metals, alloys, intermetallic compounds, and, in rare cases, nonmetallic compounds, that when cooled to low temperatures suddenly and completely lose all resistance to the flow of electricity: once a current is caused to flow in a superconducting circuit, it will flow literally forever without sensible diminution, so long as the circuit is kept cold enough. Different materials undergo this transition from the normal to the superconductive state at various so-called critical temperatures T_c. The highest generally accepted T_c found to date is about 23 K for the compound niobium-germanium (Nb_3Ge), whereas the earliest work with superconductors such as mercury, lead, tin, etc., showed these materials to have T_c lower than about 7 K and to revert, at temperature below the respective T_c's, to the normal state when only modest currents or magnetic fields were impressed upon them (these materials have since been called "Type I" superconductors). Since the late 1950's, however, new superconducting materials (Type II superconductors) have been discovered, which have higher T_c and can remain superconducting while carrying huge current densities (up to 10^7 A/cm^2) or while exposed to exceedingly high magnetic fields (up to 45 T). A "superconducting phase diagram" typically appropriate for these new materials is given in Fig. 1, where the current J and magnetic field H are plotted as functions of temperature T and where the phase boundaries represent critical current density $J_c(T)$ and critical magnetic field $H_c(T)$; the volume above the curves represents the normal resistive state, while that below is the superconducting state. At T_c both H_c and J_c are zero but increase as T decreases, so that in applying superconductors in practical devices the rule-of-thumb has been to operate the devices only at $T < 0.75\ T_c$.

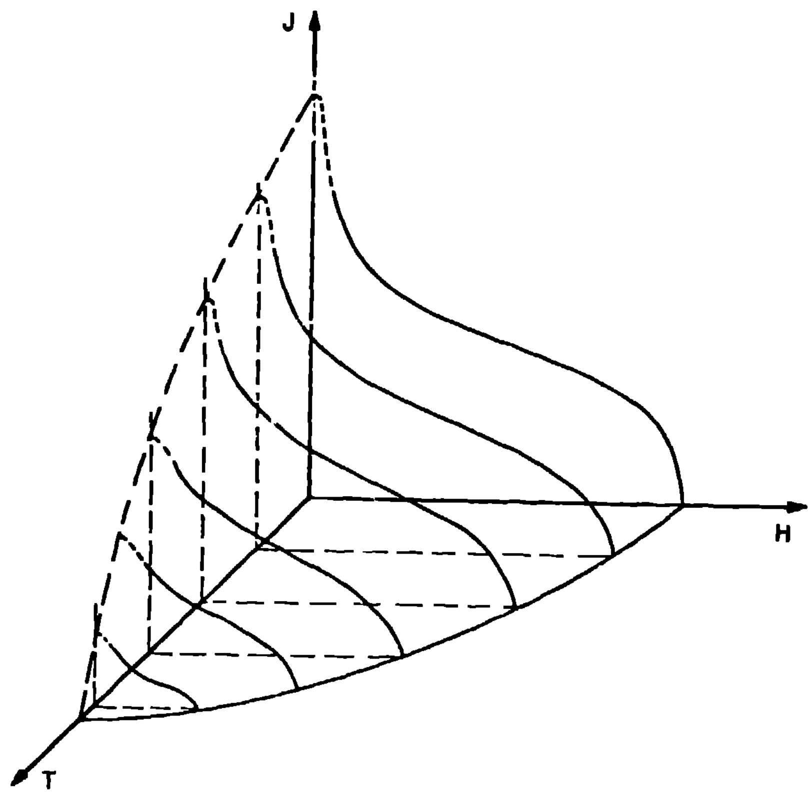

Fig. 1. Plot of critical current density J_c and critical magnetic field H_c as functions of temperature T for a typical Type II superconductor.

A considerable effort is often required to make the metallurgical transition from laboratory samples of superconductors to suitable conductors for various devices. In order to stabilize the superconductor against thermal, electrical, and magnetic disturbances it is necessary to form composites with high conductivity normal metals such as copper (Cu) and aluminum (Al). It has been generally found that as the T_c of the superconductor increases, the material becomes more brittle, the metallurgy becomes more complex, and the manufacture and handling of the composite conductor becomes more difficult. Nevertheless, we have today two widely used commercially produced superconducting conductors:

1) the alloy niobium-titanium (Nb-Ti) with $T_c \sim 9.5$ K, a ductile material usually made as many (up to 150,000 or more) fine (as small as 5 μm in diameter) filaments embedded in a Cu matrix; and 2) the compound niobium-tin (Nb_3Sn) with $T_c \sim 18$ K, a brittle material commonly manufactured as thin ribbons and more recently in the multifilament form stabilized by a Cu matrix. The U.S. superconductor industry works closely with the laboratories developing superconducting devices and is continually improving and making more sophisticated its products in response to the demands of the users. These users have been supported predominantly by the Federal Government, but the industry is gearing up to produce the expected larger orders when superconducting devices become items of commerce.

A central problem in the development and use of large-scale superconducting equipment concerns the necessity to cool down that equipment initially, to maintain it at appropriate low temperatures, and to remove the Joule (I^2R) heating from normal metal current leads to the superconducting units. Given the present practical superconductors, NbTi and Nb_3Sn, which would be useful only at temperatures less than about 13 or 14 K, we find that helium (He), with a normal boiling point of 4.2 K and a critical point of 5.2 K, is the only available fluid to serve as a refrigerant and heat transfer medium. Helium liquefiers and refrigerators are commercially available in sizes of up to 1000 W (at 4.2 K) and extension to 5000 W, about the largest capacity that appears to be needed, should offer no serious problems. Reliability and efficiency are, however, parameters that still require improvement; but under the promise of a developing superconducting technology, increased attention is being directed towards introducing new and more efficient refrigeration cycles and components. Because a higher operating temperature allows a higher efficiency for a given type of machine, there is considerable motivation for seeking superconductors with higher T_c and, at least, for making practical superconductors using Nb_3Ge. In the latter instance it would be feasible for many applications to use hydrogen (freezing point 13.8 K) as the refrigerant or heat transfer fluid. The development of Nb_3Ge conductors is under way at LASL and elsewhere.

We are now in a position to appreciate why superconductivity technology appears attractive from both technical and economic aspects. Because superconductors can pass exceedingly large currents without electrical loss and through a relatively small cross-section of conductor, they should be useful for producing more efficient, more compact and higher capacity equipment than could be obtained from using normal metal conductors. The trade-offs for these benefits vis-a-vis those of the conventional counterpart equipment must be made largely in terms of the cost, viability, and extra complications associated with the unusual materials and refrigeration requirements for superconducting devices. It is the fact that these are now well in hand that causes us to be optimistic about the near-term application of superconducting technology.

In the case of power transmission, the capacity (proportional to current times the voltage) of conventional systems is current-limited by the size (cost) and thermal rating (I^2R losses) of conductors and is voltage-limited by environmental and electrical insulation considerations. A dc SPTL, however, would exploit the large current-density characteristics of superconductors and could carry, in a single circuit at relatively low voltages, 10,000 MW or more - enough to power the entire city of New York. Such a line would be underground and would be extremely efficient as it would suffer no I^2R losses. We will consider these points in more detail in the next section.

Because the energy E stored in a magnet is proportional to the inductance L times the square of the current in the coils (i.e., $E = 1/2\ LI^2$), by increasing the current through the use of superconducting coils it becomes possible to store huge amounts of energy in relatively small volumes. As in the case of the dc SPTL, a SMES device for electric power application would be underground and would have a higher efficiency than other technologies either in use or proposed for this purpose, as we shall discuss more fully later.

III. DC SUPERCONDUCTING POWER TRANSMISSION

The problem of transporting large amounts of electric power from a generation site far from the load center is at present being addressed in a preliminary yet serious manner. The Philadelphia Electric Company (PECO) has anticipated a need in the 1990's for a system to transmit 10,000 MW underground from a park (Peach Bottom site) to downtown Philadelphia 106 km away. Under the auspices of the U.S. Energy Research and Development Administration (now Department of Energy) PECO has investigated the electric system and cost aspects of some 15 different types of underground transmission systems proposed and submitted by independent organizations. The LASL dc SPTL design for the PECO situation can serve as the focus for our discussion for dc superconducting power transmission.

Figure 2 shows a cutaway drawing of the LASL dc SPTL coaxial monopole cable design for a nominal 5,000 MW capacity at 100 kV and 50 kA. Other power, current, and voltage levels can be easily accommodated within this geometry through compatible changes in component diameters. For example, for the PECO study, our analysis for optimizing the economic choices while satisfying the electrical system requirements in-

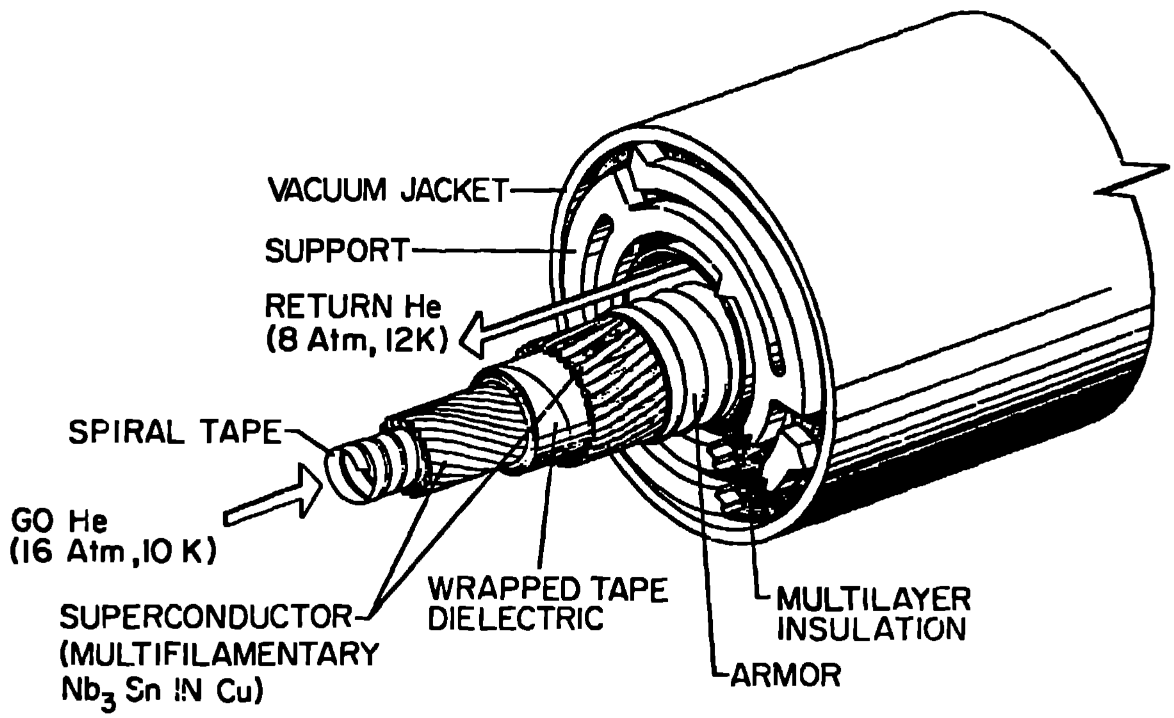

Fig. 2. Cutaway drawing of LASL dc SPTL cable design. For operation at 100 kV and 50 kA (5,000 MW), outside diameter of enclosure would be approximately 290 mm.

dicated that three 7,500 MW lines would be needed and that operation at 300 kV and 25 kA would be most economical. These parameters caused the outside diameter of the cable to increase to 330 mm from the 290 mm given for the 5,000-MW cable of Fig. 2.

The cable itself provides complete circuits for both the refrigeration and the electrical power. Helium refrigerant passes from a line refrigerator through the core of the cable to a far-end expander; after expansion the fluid exits to the annulus between the cable armor and the inside of the cryogenic envelope and then returns to the refrigerator. In this counterflow process the far-end expander acts as a final expander for the refrigorator, even though the two machines may be separated by a long length of cable. Depending upon the actual situation, refrigerators would be spaced from 5 to 30 km apart (10 km in the PECO case) with turbine expanders placed about midway between.

Multifilamentary Nb_3Sn in Cu matrix has been chosen as the superconductor with a view towards facilitating fabricating of joints, enhancing the current-sharing properties of the conductor (unless the strands are transposed, currents in the outer layers of conductors will shield the inner layers and cause uneven current distributions), and increasing the mechanical strength and handling characteristics of the wires. The inner winding of conductor carries the full current at the high voltage, while the outer windings carry the same current at neutral potential, thereby completing the circuit. Electrical insulation between the inner and outer layers of superconductor is provided by a wrapped tape dielectric rated to withstand 20 MV/m before breakdown.

A corrugated pipe encloses the cable and serves both as a dividing barrier for the go and return helium streams (the layers of conductor and electrical insulation are permeated by the helium) and as a mechanical binder and protector of the cable. The cryogenic enclosure surrounding the cable consists of two pipes held concentric by spacers; superinsulation (thin aluminum-coated Mylar) is wrapped around the inner pipe and the space between pipes evacuated. With this thermal isolation, the heat in-leak at 10 K should amount to about 0.25 W/m of cable.

In installing the transmission system, we would expect to construct 30-m lengths of the cryogenic envelope in a factory. These would be transported to the transmission corridor, joined there in the field, and laid in appropriate trenches. Similarly, the cable would be manufactured in lengths up to 600 m, taken to the field and drawn through the already-laid cryogenic envelope. These procedures are similar to those now used by the cable industry and illustrate how the design of the LASL dc SPTL was drawn so as to take advantage of as much of present day cable technology as possible.

Laboratory work at Los Alamos is separated into three areas: cable engineering, low temperature dielectric studies, and refrigeration and enclosure development - naturally there are numerous close interactions among these. It is planned that the three areas should be brought together in the construction of an approximately 200-m prototype demonstration of a nominal 5,000-MW line by about 1982. This demonstration would be designed to be sufficient for electric utility acceptance testing. Progress in the experimental engineering program is now at the stage where the technical feasibility of the dc SPTL is firmly established.

The PECO study, in turn, has provided good evidence that the dc SPTL could be comfortably integrated into the U.S. electric power grid. Although the final report is still in preparation, a number of other advantages of the dc SPTL have become clear from this study. Of all the underground technologies considered, the dc SPTL was expected to show the lowest line losses - these losses amount to 0.18% of the power transmitted and arise solely from the power required to keep the 106-km length of line (3 lines) at 10 K. In terms of capital costs, the dc SPTL line was found to have the second lowest cost per meter, just slightly more expensive than a conventional 600-kV dc self-contained oil-filled cable. In considering the total transmission system, including terminals, the dc SPTL was estimated to cost $1.69 B, compared with the lowest estimate of $1.31 B for the ac SPTL and the highest estimate of $2.69 B for a resistive cryogenic cable; in all, six of the 15 systems considered appear to be less expensive than the dc SPTL. The main source of high costs for the dc lines is the terminal equipment - ac-dc converters and inverters. These have not received much attention from the industry because so few dc applications are now in use. But the virtues of dc power systems for grid stabilization and asynchronous ties is becoming better and more widely appreciated; hence it is not unreasonable to expect to find declining costs and increasing efficiencies for dc terminal equipment over the next decade or so - these expectations are fully shared by the manufacturers. It should also be noted that the dc terminal cost is independent of line length. Hence some crossover lengths (depending on power, terrain, etc.) should exist where the dc system becomes less costly than the corresponding ac system. Such crossover lengths are indeed moving targets, but they appear to be moving in favor of the dc systems.

The PECO study represents the first time so many different underground transmission technologies could be compared on a relatively uniform basis. It also represents the first "real world" evaluation of the LASL dc SPTL. It is certain that all parties concerned have gained insight and information on how a new technology might be introduced for the benefit of a society which demands abundant, inexpensive, reliable, and safe electric power without sacrifice of environmental integrity.

At LASL we have already begun to think of variations of dc SPTL design that will reduce still further the line costs. One design that holds considerable promise is a bipolar line with ground return intended for operation at ±600 kV and 6.25 kA to provide 7,500 MW capacity. The conductors are Nb_3Sn ribbons soldered to copper rods; electrical insulation is placed on the outside of the cryogenic envelope and remains at ambient temperature; the flow of refrigerant is unidirectional in each cable (rather than counter current). Estimated costs of this line for the PECO mission are about 75% of those for the coaxial monopole. One advantage of the latter, however, is that the current magnitudes and directions in the high voltage and neutral return conductors combine to produce zero electric and magnetic fields outside the cable armor. On the other hand, although for the bipolar line the field cancellation is not complete, the residual fields should be manageable. It is this sort of trade-off - costs versus functions - which must continuously be made in order to achieve acceptable high power transmission systems.

IV. SUPERCONDUCTIVE MAGNETIC ENERGY STORAGE

The operation efficiency of a power-park-to-load system could in most cases be significantly enhanced if it were to incorporate an appropriate energy storage system. Most power sources, and especially nuclear reactors, are most efficient if run at a constant level of output, while load demands vary seasonally, weekly, and daily, often by as much as a factor of two or more. Energy storage capability located near the load center would be beneficial for storing energy during off-peak demand periods and for delivering energy during peak demand periods. Also, for cyclic power sources, such as solar, energy storage is required to satisfy the load demand variations.

Energy storage in amounts of 10,000 MWh and upward must be considered for use in conjunction with energy parks. At present pumped hydrostorage is the only technology available to satisfy such requirements. This method, however, has several drawbacks: first, limited availability of locations having adequate water supply plus suitable terrain as well as strenuous objections from those concerned with the environment have, in the past, often made it exceedingly difficult to site pumped hydro systems where they are needed - there seems to be little expectation of reversing these factors; second, pumped hydrostorage is overall about 70% efficient; and third, start-up times are often slower than desired. It is not surprising, therefore, that other storage methods are being sought, and among the technologies now being developed are: high performance batteries, underground pumped hydrostorage, compressed gas storage, flywheels, thermal oil or steam, and superconductive magnetic energy storage (SMES). Of these, SMES probably requires the most development but, at the same time, probably holds the most promise for supplying the needed storage in the most acceptable manner. The advantages we foresee for SMES vis-a-vis other energy storage systems can be summarized as follows in that SMES is expected to be:

- Highly efficient - up to 95% for energy in/energy out.
- Cost effective - capital and operating costs are estimated to be competitive with other storage technologies.
- Easily integrated into the electric power grid - because the energy stored is electromagnetic, conversion from potential, mechanical, or chemical energy is not required.
- Capable of rapid response to energy demands - full power is available in a few milliseconds, so SMES units can provide spinning reserve and system stability.
- Sitable near load center - SMES units will be placed underground and will produce minimal environmental hazards.
- Reliable and safe.

The principles of how a SMES system would interface with an electric power grid are illustrated in Fig. 3. As power in the U.S. electric grid is generated, transmitted, and distributed almost entirely in the ac mode, Fig. 4 shows the 3-phase bus as the source. But whether the grid is ac or dc, it would be necessary both to transform the relatively high-V and low-I power from the bus to low-V and high-I power in the magnet and to interface the SMES system through converter equipment: a line-commutated

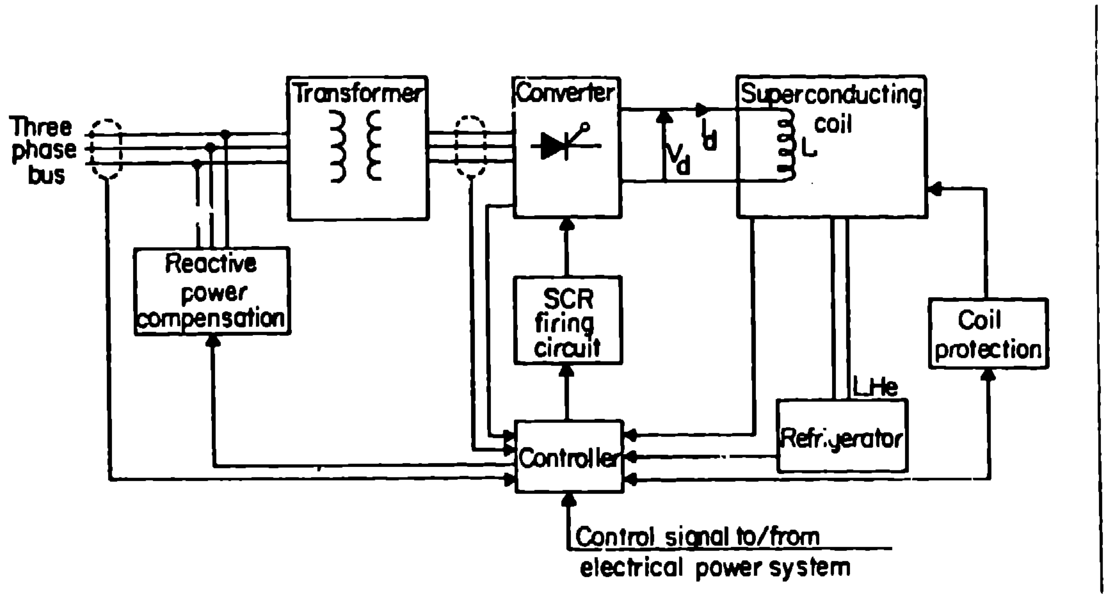

Fig. 3. Line diagram of SMES interface system with a three-phase electric power bus.

converter with thyristor switching elements controls the power flow between the magnet coil and the grid. To charge the coil, ac power from the grid is converted to dc; and to discharge, the sign of the voltage across the thyristor bridge is reversed and produces the inversion from dc to ac. Laboratory tests at LASL using a 12-pulse Graetz bridge, as in utility system operation, have demonstrated that full power reversal, from ac to dc or dc to ac, can be accomplished in less than 7 ms. In the storage mode, the current circulates in the superconducting coil without suffering electrical losses. The total losses for the system include those in the converter, about 1.2% for each passage, and the power required to refrigerate the coil. The latter losses depend on the duty cycle of the system but can be as low as 3% of the energy exchanged.

As contrasted with the situation for the dc SPTL, where it is advantageous to use a superconductor with as high a T_c as is consistent with the material handling properties, for the SMES system the economics favors the use of Nb-Ti cooled to low temperature, about 1.8 K. Although at 4.2 K (the usual approximate operating temperature for devices cooled by liquid helium) Nb-Ti carries less current density than Nb_3Sn, it is also considerably less expensive per ampere-meter. Furthermore, by additional cooling to 1.8 K, the current density in Nb-Ti can be increased by nearly 50%, thereby essentially doubling the energy storage capacity for a given coil. The complication of operating at 1.8 K increases somewhat the cost of the refrigeration system, but still allows more energy to be stored per dollar than would operation at 4.2 K. In addition, at 1.8 K, liquid helium is in the superfluid state, and therefore provides a much better heat transfer medium than boiling helium at 4.2 K.

Figure 4 illustrates how the schematic of Fig. 3 might be reduced to practice for a 10,000-MWh SMES system to provide diurnal peakshaving for a load center (upper right - the generation plant is indicated at the upper left). The storage coil is a solenoid, approximately 300 m in

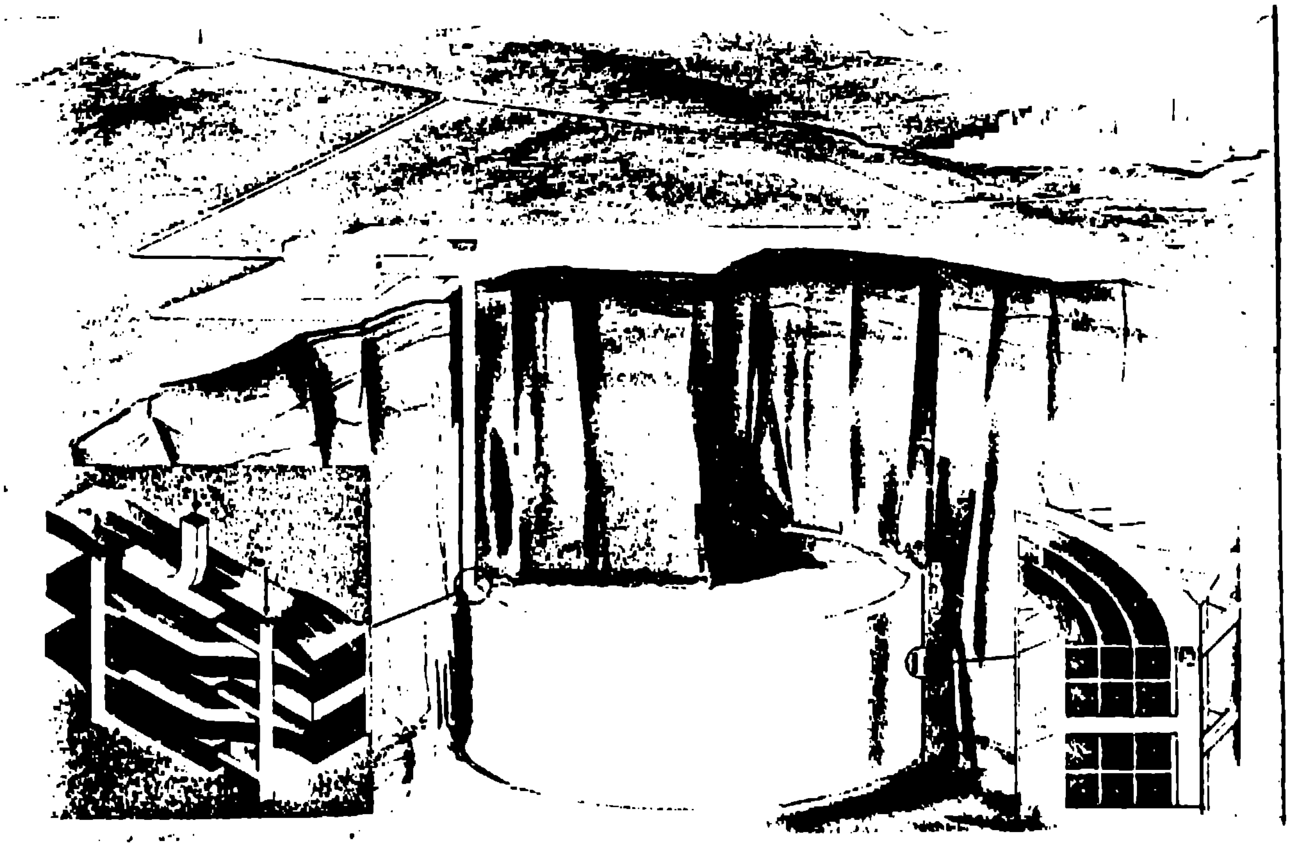

Fig. 4. Artist conception of a 10 000-MWh SMES system.

diameter and 100 m high, charged to produce a maximum magnetic field of 8 T (80,000 G) at the coils. The forces generated by such large fields generate an outward pressure, much like the case of a pressure vessel, which must be contained and supported. One method of obtaining this support would be to apply massive amounts of some strong material, such as stainless steel, kept at low temperatures. This, however, would be prohibitively expensive. Instead, the coil is to be placed underground to take advantage of the bedrock structure to support the coil. This scheme requires the use of strong, low-thermal-conductivity struts extending from the cold coil to the ambient temperature rock, all within a cryogenic enclosure, or large dewar vessel. One representation for this support structure is shown in the right inset of Fig. 4. Cooling of the coil, by refrigerators on the ground surface, can be accomplished by pool boiling of the liquid helium in the dewar or, as shown in the left inset of Fig. 4, by forced flow through a hollow conductor. In any event, provision must - and can - be made for slowly and safely deenergizing a coil should the refrigeration system malfunction or, if for any other reason, the coil should pass irreversibly into the normal, resistive state.

Although SMES technology has not advanced to the stage at which a 10,000-MWh device can be constructed, it is possible to visualize such a device being designed, manufactured, and installed using present-day commercial techniques. It is, therefore, also possible to provide some fairly reliable cost estimates for comparison with the world's largest pumped hydrostorage plant, at Ludington, MI. The latter was constructed over the years 1968 to 1973 at a cost of $300M, actual dollars. To replace this plant by a SMES unit, including refrigerators, transformers, and converter equipment, we estimate the cost would be $380M in 1977 dollars. (At an annual average inflation rate of 8% over the four years 1973 to 1977, the

Ludington plant would cost $408M in 1977 dollars.) In addition, because SMES would operate at a conservatively estimated efficiency of 90% vis-a-vis an efficiency of 70% for the pumped hydro plant, the power generation plant for SMES could be about 20% smaller than for Ludington: a reasonable generating source for Ludington is 2,000 MW_e and, thus, for SMES 1,600 MW_e; at a cost of \$800/kW_e this represents a possible additional capital saving of $320M for SMES over Ludington, and in terms of fuel a saving of 10 M barrels of oil per year!

The LASL is planning a staged development of SMES systems. Using a magnet storing 100 kJ (28 Wh) of energy we have interchanged energy with the local power system in a demonstration of the principles of SMES and, in particular, of the rapid response (6-7 ms) of the converter system. The next stage, now under construction at LASL -- albeit at a pace slowed by funding constraints - is a 100-MJ (28 kWh) inductor, which can be fully charged or discharged in 100 s, i.e. at a power of 1 MW. This system will also tie into the local 20-MW grid. The 100-MJ device is designed to test all phases of large-scale SMES system operation except for the concept of rock support - it is too small to provide meaningful information about this aspect. Following successful experiments with the 100-MJ unit, we would expect to engage in the cooperative construction efforts (with the Department of Energy and industrial concerns) of an approximately 3.6×10^4-MJ (10-MWh) device at an electric utility company site. This demonstration could prove the rock-support concept and serve a useful system stabilization function for the grid - and in fact, several electric utility companies have expressed interest in this device for stabilization purposes. With appropriate funding, this system could be on stream in the late 1980's and could lead to 5,000 MWh and larger units by the 1990's.